Investigating Trojan Asteroids at the L4/L5 Sun-Earth Lagrange Points.

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Introduction: Investigations of Earth's Trojan asteroids will have benefits for science, exploration, and resource utilization. By sending a small spacecraft to the Sun-Earth L4 or L5 Lagrange points to investigate near-Earth objects, Earth's Trojan population can be better understood. This could lead to future missions for larger precursor spacecraft as well as human missions. The presence of objects in the Sun-Earth L4 and L5 Lagrange points has long been suspected, and in 2010 NASA's Wide-field Infrared Survey Explorer (WISE) detected a 300 m object [1]. To investigate these Earth Trojan asteroid objects, it is both essential and feasible to send spacecraft to these regions.

By exploring a wide field area, a small spacecraft equipped with an IR camera could hunt for Trojan asteroids and other Earth co-orbiting objects at the L4 or L5 Lagrange points in the near-term. By surveying the region, a zeroth-order approximation of the number of objects could be obtained with some rough constraints on their diameters, which may lead to the identification of potential candidates for further study. This would serve as a precursor for additional future robotic and human exploration targets. Depending on the inclination of these potential objects, they could be used as proving areas for future missions in the sense that the delta-V's to get to these targets are relatively low as compared to other rendezvous missions. They can serve as platforms for extended operations in deep space while interacting with a natural object in microgravity. Theoretically, such low inclination Earth Trojan asteroids exist [2]. By sending a spacecraft to L4 or L5, these likely and potentially accessible targets could be identified.

Trojans and Co-Orbiting Objects at Lagrange Points: A Trojan asteroid shares an orbit with a planet or large moon, and orbits around one of the two stable Lagrange points. Trojan asteroids do not collide with the co-orbiting object because they lie 60° ahead of (L4) or behind (L5) the larger body's orbit. The presence of natural objects in Lagrange points is not uncommon. Based on the presence of Trojan asteroids in Lagrange points near Mars, Jupiter, and Neptune [3,4,5], it was suspected that Earth could have similar co-orbiting objects. The Sun-Neptune L4 and L5 points are heavily populated with objects called the Neptune Trojans. Saturnian moons Tethys and Dione each have two objects at their L4/L5 points. Mars has at least three asteroids co-orbiting at its Lagrange points. WISE searched the sky for near-Earth objects and discovered Earth's first, and to date only-known, Trojan asteroid – 2010 TK7 [1,6]. In the Sun-Earth system, it is very possible more objects will be discovered in the L4 and L5 stable points [7]. At L1, L2, and L3, natural objects will eventually be removed from these regions due to gravitational perturbations; therefore, it is unlikely to detect objects here. However, Sun-Earth L4 and L5 are points of quasi-stable equilibria, making it more likely to find objects at these points or librating around them.

Earth's First Trojan Asteroid: It is challenging to detect Earth co-orbiting asteroids from the ground because their viewing geometries due their locations with respect to Earth tend to place them in the daytime sky. NASA's WISE space telescope was launched into a 97.5° Earth orbit and scanned the entire sky 90° from the Sun. NEOWISE was an extension of the WISE data processing system. Among its identification of over 500 near-Earth objects, NEOWISE revealed two potential co-orbiting objects, including a horseshoe orbiter (2010 SO16) and a Trojan asteroid (2010 TK7) [6].

2010 TK7 was suspected to be a Trojan asteroid based on the orbital positons that were measured for a six-day arc [1]. Telescopic observation made in Hawaii improved the knowledge of its orbit to the extent that it was confirmed to be a Trojan asteroid. 2010 TK7 exhibits a tadpole motion consistent with that of Trojan asteroids. A one-year average curve of the object's motion shows it librating about L4. 2010 TK7 has a large eccentricity of $e = 0.191$ producing an annual heliocentric radial motion between 0.81 and 1.19 AU. Its inclination is $i = 20.9°$ indicating substantial motion that is perpendicular to Earth's orbital plane. The eccentricity and inclination create a large epicycle, making it visible to WISE at the solar elongation of 90°.

Finding Additional Earth Trojan Asteroids: Several studies have been done to estimate the probability of finding more Earth Trojan asteroids [8, 9]. Dvorak et al used analytical mapping and numerical methods in dynamical models. By taking into account clone orbits, the capture and escape of Trojans, and the stability region of the Lagrange points, they predict that other Trojan asteroids exist at Earth's stable Lagrange points [8]. Mikkola and Innanen performed numerical integrations to demonstrate that there exists stable, 1:1 resonance, asteroidal orbits for Earth [9].

Why Visit Trojans? Earth co-orbiting objects such as Trojan asteroids could make ideal candidates for near-term low velocity fly-bys and rendezvous missions. Visiting Trojan asteroids would not only be pertinent to the scientific and exploration goals of NASA, but could also be advantageous logistically. The low-gravity of these objects makes them ideal as proving areas for future asteroid mission technologies. The potential delta-V required to get to these objects could be substantially lower relative to other nearby objects of interest. Currently, the only known Earth Trojan asteroid, 2010 TK7, has such a large inclination (20.9°) that the delta-V required (9.4 km/s) would make it challenging to visit [1]. However, the absolute magnitude, diameter, and assumed albedo of 2010 TK7 indicate that it is comparatively large among near-Earth asteroids [1]. It is very possible that more Earth co-orbiting objects exist in the L4 or L5 Lagrange points that have yet to be discovered, possibly due to their low albedo. Some of these objects may have inclinations that require more reasonable delta-V's such that a spacecraft rendezvous mission would be attainable. If such objects are discovered, they could also be used for in-situ resource utilization given suitable compositions (e.g., volatile or water-rich objects) or for future targets for human exploration.

Engineering Considerations: Earth Trojans share Earth's orbit and have minimal gravity, making them relatively accessible targets. A consideration in any mission is the required delta-V to get there. While the 9.4 km/s delta-V requirement for known Earth Trojan 2010 TK7 makes it less than ideal, there is the potential existence of objects at lower inclinations requiring more easily attainable delta-V's. Another consideration is communication and data relay. To ensure retrieval of the images and data from distances this far will require a high gain communication system. Additionally, while the spacecraft will need to protect against radiation, its orbit will also provide the ability to use solar power. A mission to an Earth Trojan will thus need to take into account launch vehicle, payload and instruments, size of spacecraft, and orbital mechanics considerations. An example mission is suggested below.

A Mission to L4: A small 6U CubeSat could be launched as a secondary payload on a rideshare program. The mission concept assumes the launch providers can perform an escape burn with their upper stage after deployment of their primary payload. The spacecraft would have an IR wide field of view camera and a small micro-ion propulsion system capable of about 200 m/s delta-V for course correction or further maneuvering. Assuming the launch vehicle provides the escape velocity, the small spacecraft could get to Sun-Earth L4 (or L5 on another launch) from either a low inclination launch (e.g. Eastern Test Range) or a polar launch (e.g. Vandenburg). The IR camera would look for trapped asteroids that may be too small or too dark to detect from Earth surface observation. A small high gain deployable antenna system would then be used to transmit images and data.

Conclusion: It is feasible that low inclination Earth co-orbiting objects reside at the Sun-Earth L4 and L5 points. Numerical and dynamical models suggest it is likely. Searching for the objects from the ground is not realistic, and space telescopes will only discover objects under the right lighting, object albedo, and object size conditions. To truly investigate Earth Trojan asteroids, a near-term, inexpensive spacecraft needs to visit and survey the L4 and L5 regions. In-situ characterization of Earth Trojans could yield immediate benefits in science, exploration, and resource utilization.

References: [1] Connors, M., Wiegert, P., & Veillet, C. (2011) *Earth's Trojan asteroid*, Vol. 475 pp. 481-483, Nature. [2] Stacey, R. & Connors, M. (2009) Delta-v requirements for earth co-orbital rendezvous missions. Vol 57, pp 822–829, Planetary and Space Science. [3] Connors, M. et al. (2005) *A survey of orbits of co-orbitals of Mars*, Vol 53 pp. 617–624, Planetary and Space Science. [4] Stacey, R. G. & Connors, M. (2008) *A centenary survey of orbits of co-orbitals of Jupiter*, Vol 56 pp. 358-367, Planetary and Space Science. [5] Almeida, A., Peixinho, N. & Correia, A. (2009) *Neptune Trojans and Plutinos: colors, sizes, dynamics, and their possible collisions*, Vol 508 pp. 1021–1030, Astronomy and Astrophysics. [6] Mainzer, A. et al. (2011) *Preliminary results from NEOWISE: an enhancement to the Wide-Field Infrared Survey Explorer for solar system science*, 731:53, The Astrophysical Journal. [7] Marzari, F. et al (2002) *Origin and Evolution of Trojan Asteroids*, pg. 725, Asteroids III. [8] Dvorak, R., Lhotka, C., & Zhou, L. (2012) The orbit of 2010 TK7. *Possible regions of stability for other Earth Trojan asteroids*, Astronomy & Astrophysics. [9] Mikkola, S. & Innanen K. (1990) *Studies on solar system dynamics. II - The stability of earth's Trojans*, Vol. 100 n. 1, The Astronomical Journal.